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LOW-ANGLE FAULTING

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INTRODUCTION

In the literature of structural geology it is commonly stated that rigid materials subjected to non-rotational strain tend to fracture along planes which are inclined approximately 45° to the direction of applied force. This conclusion has been developed partly from a mathematical analysis of stress and strain relations and partly from results observed in the familiar practice of crushing cubes of building stone to determine their strength. That 45° is the angle at which rigid materials normally fracture under direct compressive stress appears to be very generally accepted. This angle, therefore, has come to be regarded by structural geologists as the theoretical angle at which thrust faulting, under ordinary conditions, should occur.

But if the actual angles of dip of a large number of thrust-fault planes in the earth be tabulated and averaged, it is found that the mean inclination is less than 45° from the horizontal. According to Leith an average compiled from folios of the United States Geological Survey gives a dip of 36° for planes of thrust faults and 78° for planes of normal faults.[1] An inspection of numerous cross-sections from various other countries gives results in fair agreement with these figures. The average dip angle of thrust-fault planes, as they occur in nature, is considerably less than 45°.

While the most prevalent type of thrust-fault plane, that of the ordinary reverse fault, dips somewhat less steeply than 45°, it still does not depart widely from that governing angle. Nevertheless, in notable variation from this, field studies in the last few years have brought to the attention of geologists impressive evidence of the prevalence and the great importance of what may well be called a different genus of fault, namely, the great low-angle overthrust. Its generic characteristics are the very low inclination of its fault plane and the extraordinary horizontal displacement often attained. Such low-angle overthrust faulting has been well described, as it is strikingly shown in the Northwest Highlands of Scotland, where the Moine, Ben More, Glencoul, and other remarkable thrusts form

[1] C. K. Leith, *Structural Geology*, 1913, p. 55.

classic examples of the genus (Fig. 1).[1] In the extreme north of Sutherland the various rock groups overlying the Moine thrust plane can be shown to have been driven westward for a distance of ten miles.[2] Horizontal shiftings of comparable magnitude occurred along the Ben More, Glencoul, and other planes of thrusting which lie beneath the Moine thrust and add to the remarkable nature of the phenomena. Though since thrown into gentle folds, in many places it is clear that these planes of slippage were originally not far from the horizontal. In some other portions of the British Isles analogous phenomena have been observed.

Similarly, in Scandinavia the very intense Caledonian deformation manifested itself in horizontal overthrusting of astonishing magnitude. The vertical displacement is slight, but the horizontal slip is measured in tens of kilometers.[3]

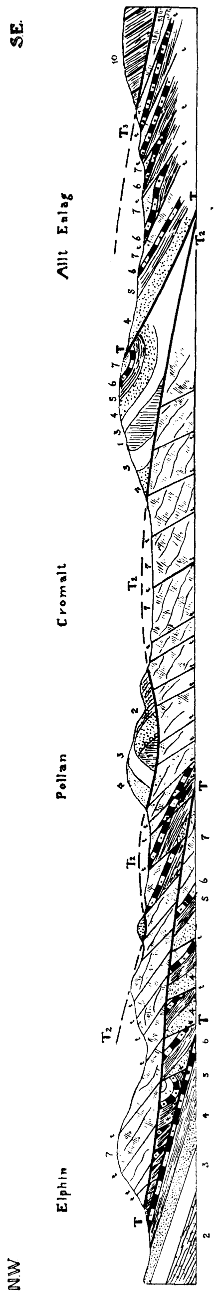

FIG. 1.—The Scottish Highland type of overthrust. Section from Elphin to Allt Ealag (about 6 miles in length). The thrust plane (T_3) near Allt Ealag on the right is the Moine overthrust. The gently folded thrust plane (T_2) which runs nearly the whole length of the section is that of the Ben More thrust. Two other major thrusts cut through the faulted slices near the left end of the section. Note the relation of the overthrusts, or major faults, to the minor reverse faults. From "Report on the Recent Work of the Geological Survey in the North-West Highlands of Scotland, Based on the Field-Notes and Maps of Messrs. B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. Hinxman and H. M. Cadell," *Quart. Jour. Geol. Soc.*, XLIV (1888), 426, Fig. 19.

[1] B. N. Peach, John Horne, W. Gunn, C. T. Clough, and L. W. Hinxman, "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. of Great Britain*, 1907, pp. 463–594.

[2] John Horne, *ibid.*, p. 469.

[3] A. E. Törnebohm, "Grunddragen af det Centrala Skandinaviens Bergbyggnad. Kongl," *Svenska Vet. Akad. Handl.*, Bd. 28, No. 5 (1896), pp. 190–95 and Pl. IV; P. J. Holmquist, "Bidrag till diskussionen om den skandinaviska fjällkedjans tektonik," *Geol. Fören. Förhandl*, XXIII (1901), 55–71.

In the southern Appalachian Mountains the Rome and Cartersville overthrusts run parallel to each other for over 200 miles. They are thought by Hayes to show horizontal displacements of not less than 4 miles and 11 miles respectively, and possibly much more. The inclination of the fault planes is here frequently as low as 5°; it is rarely more than 25°.[1] The steeper portions of the plane as now seen are largely the result of subsequent warping. Farther north, in Tennessee, a possible continuation of the Cartersville thrust is the Buffalo Mountain fault which, according to Keith, was a low-angle overthrust whose original displacement along the shear plane was at least 20 miles.[2] Subsequent folding and faulting have so disturbed this fault plane that its original inclination cannot be very closely determined.

More to the north, the earlier Taconic revolution also developed low-angle overthrusts. Of these may be noted the Great Western fault of eastern New York,[3] the St. Lawrence and Champlain fault, which runs from Vermont to the city of Quebec and beyond,[4] and possibly the Cowansville overthrust of Missisquoi and Brome counties, Quebec, though the age of the last has not been closely determined as yet. In any case the measured horizontal displacement of the last is 11 miles, and it is thought likely that the actual displacement was much greater.[5] It is a nearly horizontal overthrust, whose plane is very close to the present surface, and along which the Georgian slates on the east have been shoved over the Trenton slates and limestones of the Farnham series to the west.

The Rocky Mountains of Montana and Alberta are bordered on their eastern front, throughout at least 350 miles of their extent,

[1] C. W. Hayes, "The Overthrust Faults of the Southern Appalachians," *Bull. Geol. Soc. Amer.*, II (1891), 141–54.

[2] Arthur Keith, *U.S. Geol. Surv. Geol. Atlas, Roan Mountain* (*Tenn.*), Folio 151, 1907, p. 9.

[3] James D. Dana, *Manual of Geology* (4th ed.), 1895, p. 528; S. W. Ford, "Observations upon the Great Fault in the Vicinity of Schodack Landing, Rensellaer County, N.Y.," *Am. Jour. Sci.*, XXIX (1885), 16–19.

[4] G. A. Young, "The Geology and Petrography of Mount Yamaska, Province of Quebec," *Geol. Surv. Can. Ann. Rept.*, XVI (1906), 9.

[5] Robert Harvie, "Brome and Missisquoi Counties, Quebec," *Sum. Rept.*, *Geol. Surv. Can.*, 1914, pp. 98–99.

by great overthrusts whose planes dip in under the mountains at low angles. McConnell has estimated that on the South Fork of the Short River in Alberta the horizontal displacement of the Cambrian strata—which here rest upon the Cretaceous—has been about 7 miles, while the vertical displacement amounts approximately to 15,000 feet.[1]

In the Glacier National Park of Montana, Willis found the Proterozoic strata which make up the outermost range (here called the Lewis Range) overthrust at least 7 miles upon the Cretaceous of the foothills. The dip of the thrust plane, as determined by Willis by graphic construction, ranges from 3° to $7^\circ 45'$.[2] More recently Campbell has been able to show that where the Great Northern Railroad crosses the range this great mass of strata has been shoved at least 15 miles northeastward along the Lewis thrust plane, and were the original position of the mountain mass known the distance might prove to be much greater.[3]

At the International Boundary the northward continuation of the Lewis thrust has been termed the Waterton Lake thrust by Daly. The known extent of the bodily movement here represented is about 8 miles, as measured on the perpendicular to the line tangent to Chief Mountain and the outermost mountains of the Clarke Range. But the actual movement, according to Daly, has probably been 10 miles or more, and may be as much as 40 miles, for "it is not impossible that the entire Clarke Range (the equivalent of the Livingston Range of Willis) in this region represents a gigantic block loosened from its ancient foundations, like the Mount Wilson or Chief Mountain massifs, and bodily forced over the Cretaceous or Carboniferous formations."[4]

The Willard thrust discovered by Blackwelder in the Wasatch Mountains of Utah has a displacement, so far as exposed, of about 4 miles, though this is probably but a small fraction of its total

[1] R. G. McConnell, *Geol. Surv. Can.*, II (1886), Part D, p. 33.

[2] Bailey Willis, "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. Amer.*, XIII (1902), 331–43.

[3] M. R. Campbell, "The Glacier National Park," *Bull. 600, U.S. Geol. Surv.*, 1914, p. 12.

[4] R. A. Daly, "Geology of the North American Cordillera at the Forty-Ninth Parallel," *Mem. 38, Geol. Surv. Can.*, Part I (1912), p. 91.

displacement. Though the fault plane locally has a dip as high as 50° owing to later warping, it averages about 15°.[1]

The Bannock overthrust, recently described by Richards and Mansfield, when traced through southeastern Idaho and Utah along its course, now made sinuous by erosion, has a length of approximately 270 miles, and involves a horizontal displacement of not less than 12 miles.[2] The thrust plane itself is a gently undulating surface nowhere steeply inclined, sometimes dipping to the east and sometimes to the west. If this slight plication be the result of subsequent folding, the shear plane must originally have been very nearly horizontal.

In eastern Wyoming the Absaroka and Darby faults are really of the overthrust variety, although what remains of these planes shows a higher angle of inclination than most of the preceding.[3] The fault plane of the Darby thrust is, in general, not far from parallel to the bedding of the overthrust sheet. East of Yellowstone National Park the Hart Mountain overthrust is thought by Dake to show a displacement of not less than 22 miles, making no allowance for recession of the eastern front by erosion.[4] Assuming average thickness for the beds involved, the vertical displacement is over 6,000 feet.

In the Alps, so long and carefully studied, some of the most remarkable structures known to geologists are still in process of being worked out. As yet there is lack of perfect accord as to some of the features of their interpretation. They have commonly been interpreted as extraordinary and wonderfully drawn-out overfolds (*nappes de recouvrement*). Among certain geologists there has developed a disposition to substitute, in interpretation, overthrust sheets of the Scottish Highland type[5] for these extreme

[1] Eliot Blackwelder, "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, XXI (1910), 517–42.

[2] R. W. Richards and G. R. Mansfield, "The Bannock Overthrust, a Major Fault in Southeastern Idaho and Northeastern Utah," *Jour. Geol.*, XX (1912), 681–709.

[3] Alfred R. Schultz, "Geology and Geography of a Portion of Lincoln County, Wyoming," *Bull. 543, U.S. Geol. Surv.*, 1914, pp. 84–87, and structure sections.

[4] C. L. Dake, "The Hart Mountain Overthrust and Associated Structures in Park County, Wyoming," *Jour. Geol.*, XXVI, No. 1 (1918), p. 50.

[5] Bailey Willis, "Report on an Investigation of the Geological Structure of the Alps," *Smithsonian Misc. Coll.*, LVI (1912), No. 31, pp. 1–13; also James Geikie, *Mountains, Their Origin, Growth, and Decay*, 1913, pp. 116–17.

overfolds. If this be the true explanation, it would add to our list this remarkable structure of the Alps as a most pronounced and complicated case of low-angle faulting.

Similar structures have been reported from Spain, Euboea, the Balkans, and the island of Timor; in the last case an extensive sheet of shallow water strata, ranging in age from Triassic to Eocene, has been thrust over what appear to be deep-sea deposits of nearly the same age.[1]

Detailed studies elsewhere—practically the world over, indeed—are bringing to light overthrust faults of great displacement along gently inclined planes. This sort of faulting seems, therefore, to constitute a phenomenon of a definite, independent type. It seems to belong to a genus of its own, distinct from the ordinary reverse fault, though the two are no doubt connected by composite types that bind them together. The common reverse fault is defined by displacement along planes neighboring 45° or a little less, and is confined to more limited movement on these planes, while the great overthrusts slide along planes that approach horizontality and involve displacements of astonishing magnitude. Though each great low-angle overthrust is commonly attended by a retinue of reverse faults of lesser magnitude—a fact which suggests that there may be a kinship between them—nevertheless an inspection of any good section, as in the Scottish Highlands, shows a radical difference between the two types. Some distinctive feature seems to be added to simple straight compression to form the low-angle overthrusts.

PREVIOUS INVESTIGATIONS

Willis has divided thrust faults into four classes, the break-thrust, stretch-thrust, shear-thrust, and erosion-thrust. Of these the shear-thrust and the erosion-thrust are low-angled overthrusts, while the other two classes belong to the more common group of reverse faults. The shear-thrust is a class to cover the conspicuous Scottish Highland type, while the erosion-thrust covers a special case of alternate competent and incompetent strata in which the upper competent formation carrying the thrust is first removed

[1] G. A. F. Molengraaff, "Folded Mountain Chains, Overthrust Sheets, and Block Faulted Mountains in the East Indian Archipelago," *Compte Rendu, Congrès Géol. Int.* (Toronto, 1913), pp. 689–702.

from the crest of a broad anticline by erosion. When subjected to further lateral thrust, the upper beds on one limb of this anticline, encountering little resistance in front, ride forward over the subaërial surface.[1] Related to this form of erosion-thrust is another special type described by Hayes from the southern Appalachians.

Thus the field of the low-angle fault is not an unexplored one, since explanations have been offered for certain special types of overthrusts. The very definite explanation for the Rome and Cartersville overthrusts of the Southern Appalachians was worked out by Hayes as early as 1891.[2] The key of this explanation was suggested by the massive and peculiarly competent dolomite formations which alternate with weaker shale layers. In this

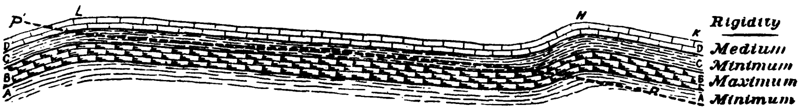

FIG. 2.—A theoretical section to represent the position of the fault plane (PP') in the Rome and Cartersville thrusts. From Hayes.

type of deformation the strata are thought to have first flexed into a pair of gentle anticlinal bends some notable distance apart. Between the flexures the strata remained essentially undisturbed. Finally a break occurred near the crest of one of the anticlines, and the thick, competent formations sheared more or less horizontally along a slippage plane which followed closely the bedding of the weak shales (Fig. 2).

The erosion-thrusts of Willis and the special form so clearly described by Hayes are dependent upon appropriate rock strata and structure, and thus these explanations, while they fit admirably the conditions in the southern Appalachians for which they were devised, do not apply to various other overthrusts where the necessary stratigraphic conditions do not obtain. They thus constitute a particular type due to special conditions. They do not apply to the very remarkable overthrusts of the Scottish High-

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., 13th Ann. Rept.*, Part II (1893), pp. 222–23.

[2] C. W. Hayes, *loc. cit.*, II (1891), 141–54.

lands, where the thrust planes cut through very heterogeneous assemblages of rock material. Different principles apparently control the latter.

It was with a view to obtaining light upon the mechanism of the Scotch overthrusts that Cadell, in 1888, even earlier than Hayes, undertook his experimental researches which since have become classic. In these instructive researches Cadell made use of a pressure box, one side of which could be thrust forward by means of a powerful screw. In this box he built up a succession of layers of plaster of Paris, interstratified with layers of sand, to imitate beds in the earth. After the plaster had set into rigid strata, lateral pressure was applied by means of the screw which moved the pressure block. In this manner, as the final outcome of many trials, he succeeded in imitating rather closely the peculiar imbricate and overthrust structure which the members of the Scottish survey were deciphering from the greatly disturbed terranes of the Northwest Highlands.[1]

Those of Cadell's conclusions which relate to overthrusting may be quoted:

1. Horizontal pressure applied at one point is not propagated far forward into a mass of strata.

2. The compressed mass tends to find relief along a series of gently inclined thrust planes, which dip toward the side from which pressure is exerted.

3. After a certain amount of heaping up along a series of minor thrust planes, the heaped-up mass tends to rise and ride forward bodily along major thrust planes.

4. Thrust planes and reversed faults are not necessarily developed from split overfolds, but often originate at once on application of horizontal pressure.

5. A thrust plane below may pass into an anticline above, and never reach the surface.

6. A major thrust plane above may, and probably always does, originate in a fold below.

7. A thrust plane may branch into smaller thrust planes, or pass into an overfold along the strike.

8. The front portion of a mass of rock being pushed along a thrust plane tends to bow forward and roll under the back portion.

9. The more rigid the rock the better will the phenomena of thrusting be exhibited.

[1] H. M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh*, XXXV (1890), 337–57.

The result of Cadell's experimentation was to produce a concrete picture of the manner in which the complex structure of the Northwest Highlands may have developed. As pressure was gradually applied, the artificially prepared strata were first sliced into separate blocks by ordinary reverse slice faults which dipped in the direction from which the pressure was applied. A piling up of the sliced blocks followed. After sufficient piling up had occurred, a low-angle major thrust plane broke through the piled-up mass of slices, and the whole overlying mass rode forward bodily upon this gently inclined plane which Cadell termed the "sole" (Fig. 3). This behavior would seem to suggest that the heaping up of material

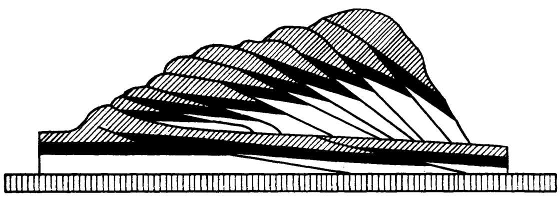

FIG. 3.—Major thrust plane, or "sole," cutting across minor slice faults. After Cadell.

is an important factor in determining the subsequent break along the low-angled "sole."

A pressure box patterned somewhat after that of Cadell was employed by Willis in his experiments upon Appalachian structure.[1] But in these interesting and well-known experimental researches folding rather than faulting was the prime object of the investigation. To obtain the desired results Willis used somewhat softer materials than those employed by Cadell, and heavily weighted the strata with a thick covering of shot to prevent too ready yielding. The hardest layers, in most cases, were composed of equal parts of plaster and wax, while the less competent beds were still further softened by the addition of turpentine, and often by leaving out plaster altogether. Fracturing occurred only very incidentally.

Further researches by Paulcke were directed toward reproducing experimentally the folds of the Jura, and the marvelous overfolded

[1] Bailey Willis, *U. S. Geol. Surv., 13th Ann. Rept.*, Part II (1893), Pl. LXVI, opposite p. 258.

and overthrust structure of the Alps.[1] With this end in view Paulcke adopted a stratigraphic series which, in most cases, comprised a thick basal layer of sand, above which were eight or nine alternating layers of clay and plaster. The mass was then weighted above by a very thick covering of sand. Because of the nature of the materials, fracturing of quite variable sorts developed—both typical reverse faults and a few low-angle overthrusts in which a strong plaster bed carrying the thrust was shoved bodily over the less competent clayey material beneath. But the brittle layers of plaster broke into numerous small rectangular blocks in addition to the major folding and faulting, and these small blocks were so rotated, shattered, and irregularly displaced as to mask much of the more significant behavior of the strata under compression. In general outlines, however, various cross-sections of the Alps were reproduced.

The experiments of Cadell suggested that the piling up of weight may be an important factor in determining the low-angle overthrusts, and that perhaps the question may be solved by experimentation. This stimulated us to attempt further experimentation in an effort to determine the influence of various contributing factors upon the angle of faulting.

METHODS OF PRESENT EXPERIMENTAL INVESTIGATION

Apparatus.—For these studies a pressure box was constructed along lines similar to those adopted by Cadell and Willis (see Fig. 4). This box differed, however, from the previous ones in having screws and movable pressure blocks at both ends, instead of solely at one end. Pressures could thus be applied from opposite directions whenever desired. But it was found, early in the progress of the work, that these pressure blocks frequently manifested a strong tendency to rise up from the floor of the box and to become tilted as the faulting of the strata progressed. To prevent this, long steel guide flanges were bolted on the inner sides of the box at a height of about an eighth of an inch above the top of the pressure block. With this control the pressure block could only move forward and backward, and the tilting of the block was thus practically

[1] W. Paulcke, *Das Experiment in der Geologie* (Berlin, 1912), pp. 74–108.

eliminated. One side of the box was constructed so that it could be removed as often as desired during the course of each experiment in order to note the nature and progress of the deformation and to photograph the structure developed. Pressures were applied by means of a $1\frac{1}{4}$-inch steel screw turned by hand, operating upon a lever arm of 24 inches. At the opposite end of the box the other pressure block was moved by a 1-inch screw. This was much less frequently used. These screws were capable of developing such thrusts that one of the chief difficulties was to secure an apparatus of sufficient strength to withstand the stresses to which it was

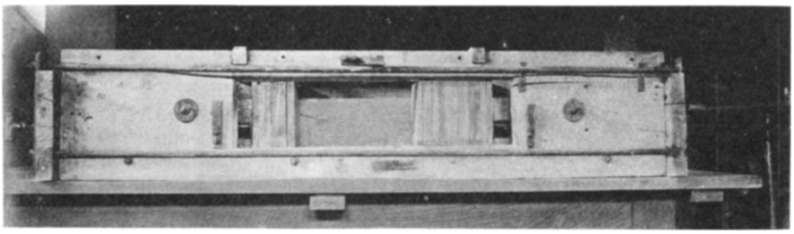

FIG. 4.—Pressure box with a movable thrusting block at each end. The detachable side has been removed to permit a view of the interior.

subjected. Various strengthening devices were employed. If another apparatus were attempted, it would be constructed entirely of steel.

Materials.—Before attempting experiments upon a succession of strata of varying competency, as would be the case in nature, it was essential to determine the effect of compressive stresses on homogeneous material. Both rigid and plastic materials were compressed in the crushing machine to determine their different behavior under stress. For rigid material either plaster of Paris or a mixture of plaster with a small amount of clay was used. As a result of many trials it was found that to secure rigid, brittle material, such as best illustrates faulting, a mixture of three parts of plaster and one part of clay gave the best results. To develop greater plasticity the proportion of clay was steadily increased, and in various cases a certain proportion of sand was added until there was as much as two parts of clay and sand to one part of plaster.

In preparing this combination it seemed best to mix the plaster and clay dry and, when thoroughly mixed, to put the mixture in the machine in that state and wet it down with water as the material was poured in. The most homogeneous mixtures were developed in this manner.

When the box was filled to the desired depth, the wet mass was allowed to set for a period of from three to seven days, until the material was not readily dented with a trowel. The length of time required depended considerably upon the combination of materials used. The greater the proportion of clay the longer the period of time necessary for the material to harden. When deemed sufficiently hard, the screw was turned and the process of crushing begun. The pressure was brought to bear gradually. After a single turn of the screw, or only a small fraction of a turn, the side of the box was removed and the resulting deformation observed. This cautious turning of the screw, with frequent halts to view the results, was maintained till the end of each experiment.

After treating structureless homogeneous materials of a considerable range of competency, tests were made with bedded homogeneous materials to discover how simple bedding planes, as lines of weakness, influenced the angle of faulting. The procedure was to place a layer of equal parts of plaster and clay in the machine, soak it thoroughly with water, and quickly smooth it with a trowel. After a few minutes, when the bed had hardened slightly, another layer of the same material was laid upon it and treated in the same manner. In this way five or six layers were built up. The whole mass was then allowed to set until rigid, and afterward crushed.

To test the influence of an alternation of beds of different competency upon the angle of faulting, Cadell's line of attack was followed at the outset. Plaster and sand were used respectively for the competent and incompetent beds. The sand was poured into the machine, bedded down, and then well dampened with water. While still wet a layer of pure plaster was added, followed as quickly as possible by another layer of sand and another of plaster, until four to six layers were built up. The plaster absorbed water at once and became hard, so that a long wait before crushing was less necessary than when clay was involved.

Troublesome difficulties arose from the use of these materials. Owing to the incoherence of the sand, the competent plaster layers, instead of rising along a single fault plane after fracturing had occurred, were thrust into the sand layers, producing a dovetail effect. Obviously it was necessary to add something to the sand to correct this and to give the sand more coherence, and yet at the same time the sand layers were to be kept relatively incompetent. With this end in view varying amounts of plaster were added to the sand and the result noted. But it was found that if sufficient plaster were added to furnish the desirable coherency, the layer became too competent for the purpose of the experiment. Clay alone was tried, but owing to the weakness of the clay, or its lack of adhesion to the plaster, dovetailing again resulted. To obviate this, plaster was added to the clay in the proportion of about two parts of clay, with some sand, to one part of plaster. This combination was successful, though in different experiments, where varying degrees of competency were desired, somewhat different proportions were used. As would be expected, the plaster layers carried the thrust, and the whole mass acted as a rigid body until these competent layers were fractured. The influence of softer layers after fracturing will be discussed later.

In certain experiments it was desired to give the competent layers somewhat greater plasticity. This necessitated increasing the plasticity of the incompetent layers as well, in order to keep the relative competency the same. For this series of experiments a mixture of plaster, clay, and sand was used for the competent beds, varying in proportion from three parts of plaster and one of clay and sand to two parts of plaster and one of combined clay and sand. For the incompetent beds either pure clay was used, or a mixture of clay and plaster varying in proportion from four of clay and one of plaster to two of clay and one of plaster. Such strata required from three to seven days to harden, depending upon the proportions of clay and plaster used.

RELATION OF FAULTS TO STRESS AND STRAIN

Stresses may be defined as the forces developed within different parts of a structure under the action of external forces operat-

ing upon it, and strain as the change in the shape or dimensions of the body resulting from stress. Strains may be dilatational, in which there is change of volume without change of form, or distortional, in which the form of the body is changed without changing the volume. Of these the latter is by far the more important in the deformation of rocks. Distortional strains may result from three kinds of stress—tensile, compressive, and shearing stress—torsion being regarded as shearing by twisting. Various combinations of these stresses are of frequent occurrence.

In the problem of thrust faulting under consideration, the deformation results from the action of compressive stresses and shearing stresses, with tension only a very subordinate and incidental factor. The operation of these stresses may be analyzed as follows:[1]

Consider a rectangular block with pressure P applied uniformly to a face to find the stress on the oblique section *mnop*.

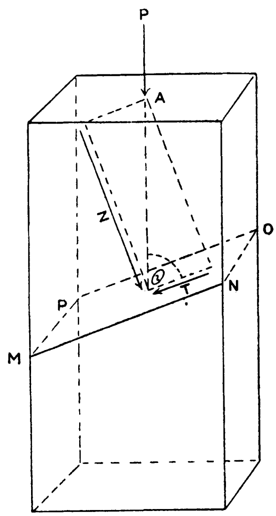

FIG. 5.—Diagram to represent the normal or direct stress (N) and the tangential or shearing stress (T) operating on an oblique section (*mnop*). The force (P) is applied uniformly on face A.

Resolve P into normal (N) and tangential (T) components. If the angle between the direction of application of force (P) and the plane of the oblique section (*mnop*) be designated θ, then

$$N = P \sin \theta$$
$$T = P \cos \theta$$

The tangential component T tends to cause sliding along the section *mnop* and is called the shearing stress. The normal component N is called the normal or direct stress.

Let a represent the area of the cross-section of the block, or column, upon which the force is applied. Then the area of the oblique section *mnop* equals $a \csc \theta$.

[1] W. C. Unwin, *The Testing of Materials of Construction*, 1910, pp. 22–23; R. J. Woods, *The Theory of Structures*, London, 1909, pp. 1–4.

Hence the stress per unit area, or the intensity of stress, on section *mnop* is seen to be:

(1) $$\text{Normal stress } (Pn) = \frac{P \sin\theta}{a \csc\theta} = P \sin^2\theta .$$

(2) $$\text{Tangential stress } (Pt) = \frac{P \cos\theta}{a \csc\theta} = P \sin\theta \cos\theta .$$

For an oblique section at right angles to *mnop* substitute $90° - \theta$ for θ and get

$$P'n = P \cos^2\theta .$$
$$P't = P \cos\theta \sin\theta = Pt .$$

Thus the intensity of tangential stress is the same on two oblique sections at right angles to each other.

The value of $P \sin\theta \cos\theta$ reaches a maximum for $\theta = 45°$ when it equals $\frac{1}{2}P$. The intensity of the shearing stress is therefore greatest for planes at 45° to the line of propagation of the force.

Since the intensity of the shearing stress is as a maximum when $\theta = 45°$, it was natural enough to suppose that fracturing under compressive stress should occur normally along planes inclined 45° to the line of application of the force, and in the familiar practice of crushing cubes of stone, cement, wood, etc., in testing machines to determine their strength for building purposes, experience is that the blocks break at angles approaching 45°, though most frequently the angle is somewhat less than this. Forty-five degrees is the angle which is commonly stated to be the angle of fracture in the geologic literature which deals with faulting and jointing under compressive stresses.

But, as has been noted, many thrust-fault planes are found to dip at angles much less than 45°, and short blocks in the crushing machine very commonly break at angles as low as 30°. Fracturing at 30° in our experiments has been commoner than at the higher angle of 45°. What is the meaning of this? Experimental error fails to satisfy the discrepancy, as an error of 15° is unlikely and the persistence of 30° and 35° breaks shows that there is some important factor, or factors, in operation which have not been considered. Let us therefore consider some of the possible factors which may operate to reduce the angle of fracture from the theoretical 45°.

FACTORS WHICH LOWER ANGLE OF FAULTING

A. EFFECT OF NORMAL COMPONENT OF STRESS

While the tangential or shearing stress ($Pt=P \sin \theta \cos \theta$) reaches its greatest intensity along planes inclined 45° to the line of application of the force P, it is also true, as has just been shown, that the intensity of the stress at right angles to this ($Pn=P \sin^2 \theta$) is likewise great. This normal stress obviously acts as a frictional resistance to shearing by the tangential stress. The value of this frictional resistance depends on the shearing strength of the material when not in compression.[1] As to the potency of this factor, Church states that the presence of compressive stress normal to the 45° plane is sufficient to strengthen the material for shearing in that plane, causing separation to occur along a plane where the compressive stress is considerably less.[2]

Let us see how this plane will be inclined. The intensity of the normal stress is expressed by

$$Pn=P \sin^2 \theta .$$

Its intensity increases as θ increases, and diminishes as θ decreases (see Fig. 6). Hence the lower the angle of the fracture plane, the less will be the frictional resistance due to normal compressive stress.

The intensity of tangential or shearing stress ($Pt=P \sin \theta \cos \theta$) is greatest when $\theta=45°$, and diminishes as θ becomes less. Shearing can occur only when this exceeds the shearing strength of the material. Here is a limiting factor.

Comparing

$$Pn=P \sin^2 \theta$$

and

$$Pt=P \sin \theta \cos \theta ,$$

it is seen that as θ becomes less $P \sin^2 \theta$ diminishes in value more rapidly than $P \sin \theta \cos \theta$ or, in other words, as the angle θ is lowered from 45°, the intensity of normal stress is reduced more rapidly than the intensity of the tangential stress. Therefore,

[1] W. C. Unwin, *op. cit.*, p. 419.

[2] I. P. Church, *Mechanics of Engineering* (New York, 1913), p. 220.

since the resistance due to the normal stress is reduced more rapidly than the intensity of tangential stress, as the angle is lowered from 45°, fracturing so far as determined solely by these two factors is made easier with the reduction of angle. But on the other hand, the intensity of tangential stress must exceed the shearing strength of the material in order to produce fracturing, and since this intensity diminishes with a lowering of the angle from 45° downward, the angle must not be too low to allow the

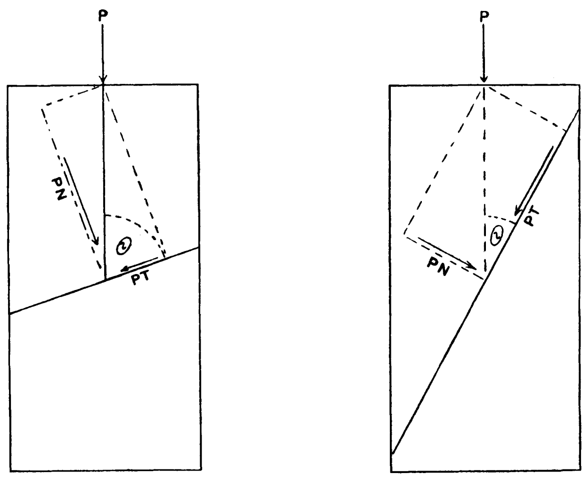

FIG. 6.—Diagrams to show how the relative intensity of the normal (*Pn*) and tangential (*Pt*) stresses on an oblique section is a function of the inclination of the section to the direction of application of the force. In the left-hand figure the direct stress exceeds the tangential in intensity; in the right-hand figure, with a lessening of the angle between the direction of the force and the plane of the section, the tangential stress is the more intense.

requisite intensity. This is the limiting factor which prevents breaking at too low an angle. The breaking plane is thus determined by a balance of these three factors. This helps to explain why homogeneous material, when subjected to compression, so persistently fractures at angles lower than 45°, although the shearing stresses reach their greatest intensity in the 45° planes.[1]

[1] A mathematical analysis leads to the conclusion that the inclination of the surface along which there is the greatest tendency to rupture is lowered from 45° by $\frac{\phi}{2}$, where ϕ is the angle of friction, or angle of repose, of the grains of the material. For

But as the favorite angles of fracturing for these blocks of homogeneous material appear to be 30°, or 35°, or 40°, the effect of frictional resistance due to the component of stress normal to the fracture plane clearly is not an adequate explanation of the great, low-angled overthrusts whose planes of fracture are commonly inclined at only 5° or 10° from the horizontal. There must be other factors.

B. EFFECT OF HETEROGENEITY OF MATERIAL

It is to be recognized that the angle of faulting is to some extent dependent upon the uniformity or heterogeneity of the material. Tests on the strength of materials seem to show that most blocks fail by a combination of shear and splitting. Only short blocks of very uniform texture will fail by shear entirely across the section in one plane.[1] Heterogeneous material which introduces differences in composition introduces irregularities in fracturing, and these irregularities are prevailingly in the nature of a lowering of the angle of fracture. But this alone will hardly explain the great overthrusts.

C. POSSIBLE INFLUENCE OF LENGTH AND SHAPE

Length.—The short column, whose length is not more than five times its diameter, fails by direct crushing. A longer column fails partly by crushing and partly by bending.[2] Thus a distinction is made in engineering practice between the behavior of the short block and the long column. The long column first bends and then splits obliquely. That the long column should be weaker than short blocks of the same material and cross-section is evident, but the theoretical treatment of its behavior is much less satisfactory than in other cases of flexure.[3] The breaking load for long columns, however, is represented by Euler's formula:

$$P=\frac{\pi^2EI}{l^2}$$

cast iron the usual value of θ is about 35°, corresponding to a value for ϕ of 20° (Arthur Morley, *Strength of Materials* [London, 1913], pp. 55–56). Hodgkinson's experiments with cast iron have shown that 35° is the common angle of rupture for this material (cited by Church, *Mechanics of Engineering*, p. 220).

[1] James E. Boyd, *The Strength of Materials*, 1911, p. 48.

[2] R. J. Woods, *op. cit.*, p. 205.

[3] I. P. Church, *Mechanics of Engineering*, 1913, p. 360.

where P is the limiting load which the column can support, E is Young's modulus of elasticity, I is the least moment of inertia, and l is the length of the column.[1]

Increasing the length, therefore, weakens the resisting power of the column and increases the likelihood of fracture.

Cubes and short blocks tend to fracture at 45°, or somewhat less. But long columns, because of the preliminary flexure, split at a lower angle. In testing the strength of cast iron in engineering practice it has been found that, as the length of the longer dimension is increased while the other two dimensions remain the same, the angle of fracture becomes lower until it reaches 30°, beyond which there is no lowering with further increase in length.[2] Experimentation upon other materials has given analogous results.

The lowering of the angle in the long column is a result of the development of rotational strain. The preliminary flexing of the column develops tensile stresses on the outer side of the bend, and at the same time develops shearing stresses by which the layers on the outer side of the bend tend to creep toward the crest of the fold. This shearing of the layers may be illustrated by bending a pack of cards. If actual fracturing occurs, the effect of the rotational couple is to lower the angle of breakage.

Earth deformation theoretically may partake of the nature either of the short block or of the long column. Except for the influence of the curvature of the surface, in most cases it would seem to parallel most closely the short block, for the dimension of the mass involved parallel to the direction of thrusting is, as a rule, less than five times the transverse dimensions of the block. The Appalachian Mountain chain is at the very least 1,800 miles in length, paralleling the Atlantic Coast. To be five times this, the northwest-southeast dimension (the length of the flexed column) would need to be 9,000 miles, or completely across North America and much of Asia. From Cincinnati to Charleston, South Carolina, on the coast, which is a most generous estimate of the distance across the deformed belt, is only approximately 900 miles. The

[1] R. J. Woods, *op. cit.*, pp. 212–13.

[2] *International Library of Technology and Mechanics* (Scranton, Pa., 1909), pp. 2–3.

vertical dimension of the vigorously deformed Appalachian block is probably less. Very likely the column need not have yielded to the deformation throughout its entire length, and so the belt actually deformed may be less than the true length of the column, but one could not safely assign to such a hypothetical column a greater length than the width of the continent. The very long Cordilleran chain would make even greater demands in this direction. Mountain ranges with their long dimension paralleling coasts from which the thrusting is assumed to have come, and with a lesser transverse dimension in the line of the thrusting, are thus to be considered as short blocks. With still less of vertical thickness involved, they are perhaps more closely analogous to the deformation of a thin prism or wall.

It is possible, however, that very locally, in a portion of a mountain range, the conditions of the long column might be operative and low-angle faulting might result, but it hardly seems likely that this principle can, in any large measure, be responsible for the great overthrusts. The most that can well be claimed for it is that it may be a contributing factor.

Shape.—The shape of cross-section of deformed masses is a factor in determining the character of the deformation which results under stress. The strength of a column depends on whether the ends are free to turn, or are fixed and thus incapable of turning. Columns with round ends bend quite differently from those with square ends.[1] The shape of a lenslike mass of sediment, weaker or stronger than the surrounding rock, may well be important in determining the nature of the deformation which takes place when the mass is stressed.[2]

D. EFFECT OF ROTATIONAL STRAIN

As designated by Hoskins[3] and applied to structural geology by Leith,[4] strains due to compression are divided into two classes—rotational and non-rotational. Non-rotational strains are defined

[1] I. P. Church, *Mechanics of Engineering*, pp. 360–61.

[2] Suggested by T. T. Quirke, personal communication.

[3] L. M. Hoskins, "Flow and Fracture of Rocks as Related to Structure," *16th Ann. Rept. U.S. Geol. Surv.*, Part I (1896), p. 860.

[4] C. K. Leith, *Structural Geology*, pp. 16–21.

as those in which the principal directions of strain remain constant with reference to the principal axes of stress throughout the deformation. Rotational strains are those in which the axes of strain are being constantly rotated with respect to the axes of stress during the deformation. The behavior of a body deformed under each of these types of strain has been admirably set forth by Leith by the use of the strain ellipsoid and the wire-netting model. As shown in Figs. 5, 6, and 7 of his *Structural Geology*, the planes of no distortion are the planes of maximum shear, and are the planes along which fracturing should tend to take place in either rotational or non-rotational strain.[1] But the inclination of these planes of shear with respect to the applied force is different in the two cases. Under non-rotational strain the shearing planes are seen to be located approximately at 45° to the direction of the applied force. Under rotational strain, on the other hand, while the relation of the shearing planes to the strain ellipsoid remains the same, the position of these planes with reference to the direction of applied force is steadily changed by rotation. In the extreme case (pure shearing) one plane of shear is seen to be parallel to the direction of the force, while the other commences at 90° to the force and is gradually lowered in angle as the deformation progresses. Fracturing is more likely to occur in the plane parallel to the force than in the one highly inclined to it.

Thus the shearing plane inclined 45° to the force in pure non-rotational strain and the corresponding shearing plane parallel to the force in extreme rotational strain may be taken as the limiting cases. It is clear that between these two limiting cases of 45° and 0° fracturing may actually take place at any intermediate angle, depending upon the relative strength of the rotational and non-rotational factors. This will perhaps be made clearer by Fig. 7.

Ellipse *A* represents the cross-section of a sphere deformed by pure non-rotational strain resulting from a uniform, horizontal compressive stress. Shearing and fracturing may occur along either of the 45° shearing planes, but more likely along plane *b* than plane *a*. In ellipse *B* the force, though still horizontally directed,

[1] C. K. Leith, *Structural Geology*, pp. 18–21.

is not uniformly distributed, but is represented as somewhat stronger at the upper end than at the lower, as indicated by the relative length of the arrows. The fracture plane (b) in consequence of the rotation of the ellipse is inclined at approximately 40° to the force. In ellipse C, with stronger rotation, the active shear plane (b) has been lowered to an angle of 25°. In ellipse D, because of still stronger rotation, the fracture plane is only 15° from the horizontal, and in E, the limiting case of extreme rotational strain, the shearing plane has reached horizontality.

Applying these principles to the earth, horizontal thrusts may therefore theoretically produce shearing planes at any angle from 45° down to horizontality, depending upon the relative strength of the rotational element in the strain. Actual faulting, however, would probably not take place exactly in these planes of maximum shear, but would, as shown on pages 17–19, be modified somewhat further by the component of stress acting normal to the shearing plane. A marked rotational strain derived from horizontally directed stresses, if it can be shown that such are likely to be developed with sufficient frequency in earth dynamics, may form a working hypothesis to explain the great low-angle overthrusts. It therefore becomes necessary to seek the conditions which might result in the development of such strongly rotational strains.

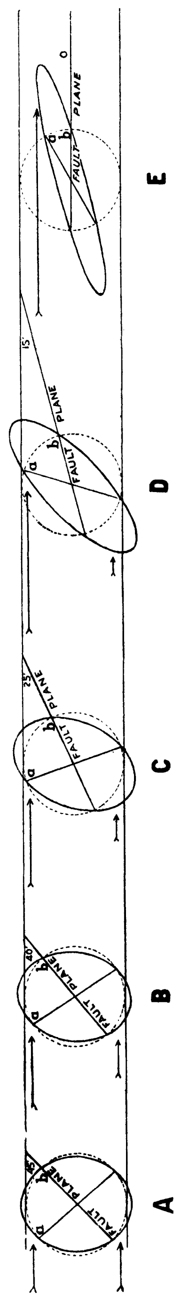

FIG. 7.—Theoretical deformation of a sphere by compressive stress. . Ellipse A, representing the cross-section of a sphere deformed by pure non-rotational strain, is the limiting case at one end. The planes of no distortion (fracture planes) are here inclined at 45°. Ellipse E, representing extreme rotational strain, is the limiting case at the other end. The active shear plane (b) is here horizontal. Ellipses B, C, and D represent cases intermediate between the two limits.

1. *Rotational Strains Developed by Bedding*

In the explanation worked out by Hayes for the Rome and Cartersville overthrusts of the southern Appalachians, the most important condition necessary for the development of such broad thrusts is stated to be the proper relation of rigidity of strata to superincumbent load.[1] An idea of the relative rigidity of the different strata in this portion of the Appalachians may be obtained from an inspection of the stratigraphic column. At the base of the exposed section are the Coosa shales which have a great, but unknown, total thickness and a minimum rigidity. Above these are several formations (Weisner quartzite, Rome sandstone, and Connasauga shale) of intermediate rigidity. These are then followed above by the Knox dolomite, a formation of unusual rigidity which consists of 3,500 to 4,500 feet of massive, cherty, dolomitic limestone almost wholly without bedding planes. Immediately upon this rest 1,200 to 1,800 feet of rigid Chickamauga limestone whose lower portion is nearly as massive as the Knox. There are, in these two formations, approximately 5,000 feet of strata with indistinct bedding and entirely without beds of shale. This gives them great competency when subjected to deformative stress. Above the Chickamauga limestone are several thin formations of lesser strength, followed by 2,500 feet of very weak Floyd shale. This very weak series is followed in turn by several formations of greater rigidity, namely the Oxmoor sandstone, Bangor limestone, and Coal Measure sandstone. This section may be generalized as follows:

D—Moderately strong sandstones and limestones.

C—Weak shales.

B—Very rigid, massive dolomites of greath strength.

A—At base very weak shales.

It is the great competency of the thick dolomites, operating in conjunction with the incompetent beds above and below, which has controlled the deformation according to Hayes.[2] Quoting from Hayes's explanation of his diagram (see Fig. 2):

As already stated, the rigid mass *B* presents its weakest points where the compressing force exerts a shear across the beds—i.e., on the sides of the folds

[1] C. W. Hayes, *op. cit.*, pp. 150–52. [2] *Ibid.*, pp. 142–44.

H and *L*. But the point *H* is in the line of least resistance, since it is nearest to the region of application of the compressing force, and hence the mass of material to be moved is less than if the break were to occur at *L*. After passing the central rigid mass the line of least resistance follows the upper bed of minimum rigidity *C* till another fold is reached where it passes through the upper rigid bed *D*. Erosion of the latter might determine the point at which the line would emerge at the surface.[1]

The requisites of this type of overthrust are thus seen to be an alternation of formations of pronounced difference in competency, affected by slight folding and possibly by moderate erosion of the upper competent layer on the anticlines before the faulting commences.

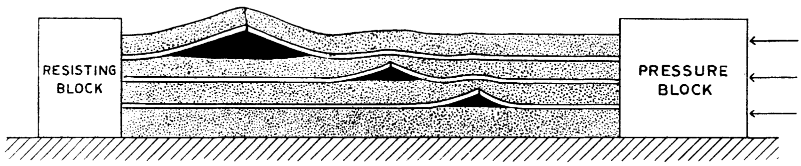

FIG. 8.—Arching up of competent layers when there is too much difference in the strength of the layers. The competent layers were composed of pure plaster, the weak layers of damp sand.

Experimentation: A single strong layer amid much weaker material.—To test experimentally some of these conclusions relative to the influence of a marked difference in the competency of neighboring layers upon the nature of their deformation, the crushing machine was loaded in the first set of tests with a single heavy, competent layer of plaster in the midst of weaker sandy layers above and below. When pressure was applied, the strong layer which carried most of the thrust commonly warped upward into a very low swell and then cracked at the top of the swell. With further compression the broken beds continued to arch up, leaving an open space below (Fig. 8). It did not appear to make much difference in its effectiveness whether the strong brittle bed were the top layer, or whether it were lower down in the series. If lower down and it was sufficiently competent, it still controlled the deformation and carried up the overlying weaker material with it.

[1] *Ibid.*, pp. 151–52.

Several strong layers between very much weaker ones.—When there were several strong layers between much weaker ones, similar arching was sometimes the result, if there was sufficient difference in the rigidity of the layers. But rather more commonly a strong tendency to dovetail was manifested. The strong and brittle beds of plaster were first thrust faulted, but in some cases the planes of faulting dipped toward the moving pressure block and in other cases away from it, thus giving both underthrusting and overthrusting (Fig. 9). After faulting commenced, the broken ends of the strong layers were wedged into the adjacent softer material, pushing it aside. Further compression caused an interwedging of

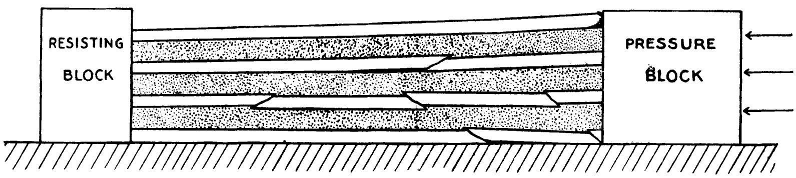

FIG. 9.—Development of dovetailing structure by both overthrusting and underthrusting when there is too much difference in the competency of the layers. With further compression the dovetailing becomes more pronounced. The strong layers were composed of four parts of clay and one of plaster; the weak layers were of damp sand.

the competent beds, producing a dovetailing structure. Dovetailing therefore results when there are a number of strong layers and the layers are too unequal in competency. This is commonly the case when there is an alternation of plaster layers and layers of damp sand. It even takes place when the competency of the strong layers is reduced by adding four parts of clay to one of plaster. This seems to be because the sand is very incoherent. When dovetailing does occur in experimentation, obviously not much is to be learned from the results so far as the present problem is concerned.

Less difference in competency.—The conditions of the last set of experiments apparently do not at all approach the conditions which control faulting in the earth. There was too great difference in the relative strength of the layers. The weak layers were too weak. For the next set of experiments sand was abandoned and only

mixtures of clay and plaster were used. Fairly good results were obtained by making the stronger layers of equal parts of plaster and clay and the weaker layers of one part of plaster to two parts of clay. There was then a working difference in competency, but at the same time not too great a difference to cause simple arching or the troublesome dovetailing.

Fracturing was found to take place at different angles across different beds. In general, it followed lower angles across the softer layers than across the stronger and more brittle ones. Perhaps the most typical result obtained is shown diagrammatically in

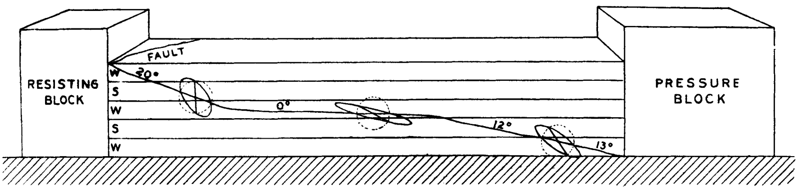

FIG. 10.—Drawing of experiment which shows how the inclination of the fracture plane may vary greatly in crossing beds of different competency. Because of the operation of a rotational strain following the fracturing of the brittle competent layers, there resulted nearly horizontal shearing through the weak, clayey layer. The strain ellipses are drawn upon the fracture line to illustrate the variable nature of the strain.

Strong layers (*S*) composed of equal parts of plaster and clay; weak layers (*W*) of one part plaster and two parts clay.

Fig. 10. When pressure was first applied in this experiment, the stronger layers carried most of the thrust, while the softer layers yielded and accommodated themselves so far as was necessary by compacting. With increasing strain the upper strong layer fractured at an angle averaging 20°, and this plane of fracture was projected through the overlying clay. With this fracturing a strong rotational strain developed below. This caused almost horizontal shearing through the soft clayey layer, where the prevailing angle of the fault plane is found to be less than 5°, and as a result of these shearing stresses the strong plaster layer below was faulted at 12°.

Bedding, therefore, where there is sufficient difference in the relative competency of the strata, may be an important factor in

determining low-angle faulting. As shown in Fig. 10, in which the ellipsoids representing the axes of strain are drawn upon the beds, the lowering of the angle in this way seems to be the result of shearing stresses and rotational strain. A difference in competency is thus one means of developing rotational strain, and the type of faulting described above comes under the category of rotational strain thus produced. The difference in competency may not be solely because of a difference in the kind of rock, but it may result also from a very unequal distribution of bedding planes which are planes of weakness. It is to be noted that an abundance of strongly marked, closely spaced bedding planes, in addition to making the competency of the formation less with respect to more massive adjacent formations, also makes splitting parallel to the bedding of the bedded rocks much easier than breaking across the bedding. With less resistance offered in that direction, fault planes crossing very thin bedded shales will be lowered to a certain extent toward parallelism with the bedding. The more bedding planes and the more pronounced they are, the lower the angle of faulting.

General discussion.—The Lewis overthrust in the Glacier National Park of Montana, according to the well-known explanation of Willis, who would classify it as an erosion thrust, appears to be a case of low-angle faulting controlled by bedding.[1] The fault plane, where observed, is located in the Proterozoic Altyn limestone, whose bedding it appears to parallel closely. Above the fracture plane, for the most part, are rigid, brittle, competent strata. What lies below the fault plane is not known, since the oldest formation in the vicinity is the Altyn limestone just above the fault plane. This has been overthrust upon the Cretaceous. In the explanation given by Willis, the sequence of events is, first, gentle folding by which there was developed a low, unsymmetrical anticline whose gentler west limb had a nearly constant westerly dip. Erosion then removed the crest of the fold, thus leaving the west limb a thick sheet of competent strata, unweakened by secondary flexures

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv.*, *13th Ann. Rept.*, Part II (1893), p. 223 and Pl. LIV, Figs. 6 and 7; "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. Amer.*, XIII (1902), 331–43.

and in a position to carry thrusts from the west. Because of the erosion of the crest of the anticline, support from the east limb had been to a considerable extent removed, and frontal resistance to a thrust from the west greatly reduced. With resistance in front lessened and resistance beneath unchanged, or very much less diminished, lateral thrusts developed shearing stresses which caused the overthrust. This type would, therefore, be an overthrust due to rotational strain fostered by the special attitude of the strata and especially by the lessening of the resistance to a forward movement of the upper layers because of preceding erosion. The shearing then took place along a bedding plane as a line of weakness.

The pretty structural explanation of the southern Appalachian overthrusts offered by Hayes was entirely dependent for its working qualities upon appropriate stratigraphic formations of widely different competency. Similarly, though to perhaps lesser degree, the erosion-thrust of Willis is dependent upon appropriate stratigraphy and antecedent history. Admitting that each of these explanations fits the particular case, or type of cases, for which it was devised (which was probably all that the authors intended), it is clear that an explanation on either of these lines cannot fit the type of overthrust which is so wonderfully displayed in the Scottish Highlands. In these remarkable dislocations the low-angle overthrusting did not occur until after the continuity of bedding over the overthrust area had been completely interrupted and displaced by repeated slice faults at the ordinary angle of 40° to 45°. The Scottish overthrusts did not follow any one weak formation, as did the overthrusts in the southern Appalachians, but cut straight through the various rocks of many previously faulted blocks. It is clear that a more general *raison d'être* for low-angle faulting must be sought.

2. *Rotational Strain in Homogeneous Material*

Piling up of material a possible factor.—One of the most characteristic features of the Caledonian diastrophism which produced the faulted structure of the Scottish Highlands was the development of a remarkable imbricate structure prior to breaking along the great thrust planes. It seems to be well established, both from the field

evidence and from Cadell's experiments, that the order of events was first slice faulting of the ordinary 45° angle type, and that, after a mass of slices had piled up in this manner, a low-angle thrust plane broke through the mass of slices and the whole mass above rode bodily forward on this plane as a "sole."[1]

Similarly it will be observed that the well-defined Rome overthrust in the southern Appalachians occurred in the midst of a

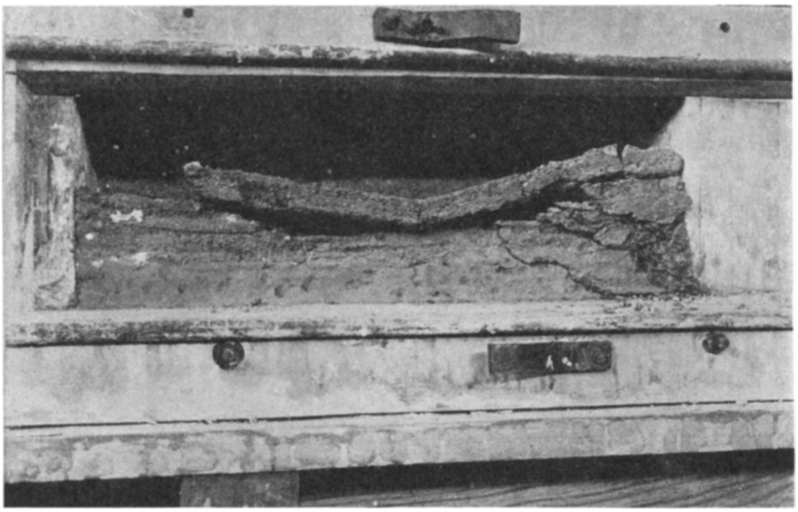

FIG. 11.—Slice faulting, developing an imbricate structure. The bottom layer was composed of pure clay; the next above of mixed sand and clay; the third was a thin layer of sand; and the heavy competent layer at the top was made of plaster two parts, sand one part and clay one part. The brittle top layer arched up and fractured as the first slice fault developed. Each successive slice fault broke out below and in front of its predecessor.

series of ordinary reverse faults. Directly south of the town of Rome, Georgia, there are mapped six large reverse faults just to the east of the line of the great overthrust. They are thus in the mass which traveled westward with the overthrust.[2] Similar slice faults in series, though they cannot be traced continuously into the par-

[1] J. Horne, "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. of Great Britain*, 1907, pp. 471–76; H. M. Cadell, *op. cit.*, pp. 347–48.

[2] C. W. Hayes, *U.S. Geol. Surv. Geol. Atlas, Rome, Ga.*, Folio 78, 1902. Structure Section Sheet.

ticular breaks near Rome, are especially numerous in the same relation to the overthrust throughout the southwest portion of the quadrangle. Somewhat analogous relations are to be noted elsewhere. Directly in front of the Lewis thrust in Montana there is represented on the structure sections a series of slice faults formed as if in preparation for another overthrust which presumably, if the deformation had been carried further, would have broken through lower than the Lewis slip and to the east of it.[1]

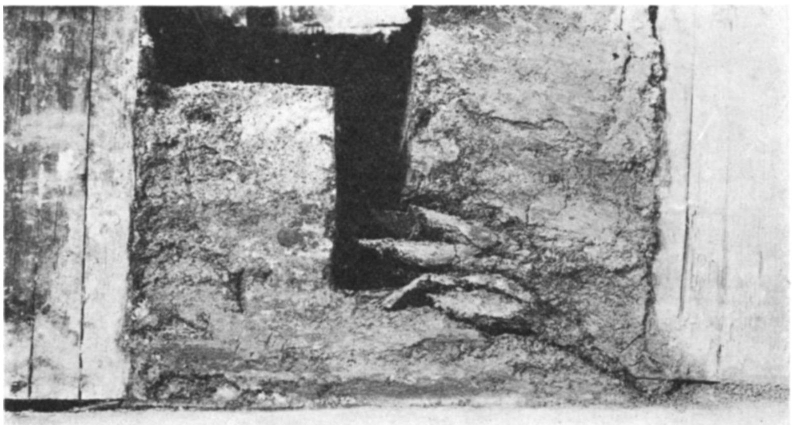

FIG. 12.—Deformation of specially shaped mass. Slice faulting resulted. In this particular experiment the pressure blocks were not held rigidly in place by controlling flanges, but were free to rise or become tilted.

A relationship between a piling up of rock masses and the development of the low-angle overthrust has therefore been suggested. It might at first seem possible that lateral thrusting applied upon the piled-up mass, thus bringing forces to bear in a higher plane than would be the case if there were no piling up, would, on the lever-arm principle, develop a rotational strain which would cause fracturing at a lowered angle. To test this question experimentally, there was molded in the box a homogeneous mixture of clay and plaster, which was high adjoining both pressure blocks and low in the middle. The rectangular

[1] Eugene Stebinger, "Geology and Coal Resources of Northern Teton County, Montana," *Bull. 621*, *U.S. Geol. Surv.*, 1916, Pl. XV.

outlines of the prepared block, by exaggerating any case of piling up likely in nature, ought not to fail to reproduce the low angles, if such be due to piled-up material acting in this way. The results are shown in Figs. 12 and 13. There was first slice faulting on the right-hand side, from which the pressure came. Each successive fault broke below the previous one as the mass was compressed more and more. This is similar to the experience of Cadell. As compression went on, the planes of the earlier faults became

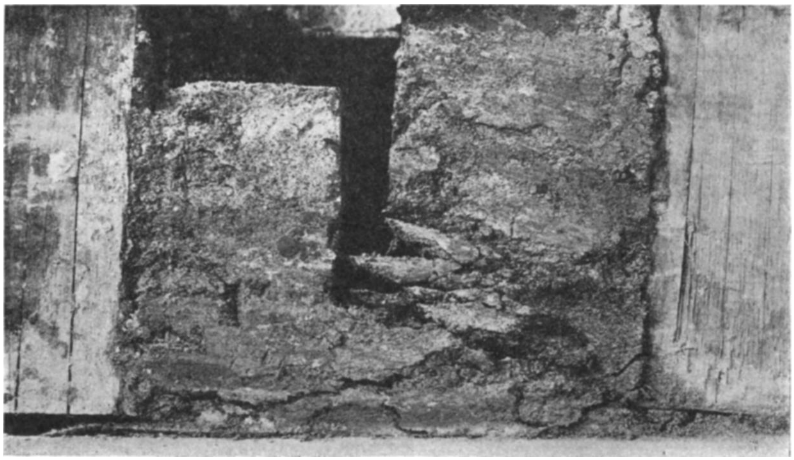

FIG. 13.—Same as Fig. 12. After further compression

distorted and obscured by the later deformation. At length a low-angle fracture broke through from the left, or resistance block side. This was no doubt determined by lines of least resistance due to weakening by the previous fracturing.

To test the matter further a mold of pure paraffine was prepared in essentially the same shape. The paraffine had the advantage of being more nearly homogeneous than the clay-plaster combination. In the two trials made, fracturing proceeded directly across the elbow at approximately 45° (Fig. 14). Lest the right-angled elbow might play an unsuspected part in determining the angle of splitting, paraffine was molded into a block having the shape shown in Fig. 15. When pressure was applied the block faulted at the farther end. It faulted at the farther end because

the force per square inch was greater there (owing to the smaller cross-section over which it was distributed) than at the other end near the pressure block where it was distributed over a larger area of cross-section. Rupture occurred where the intensity of stress was greatest, even though it was farthest removed from the pressure block. The fault averaged 42° for its whole length. The angle shows that it was caused by a non-rotational strain. The same was true also of the two previous tests. The shape of the block, at least to the extent of the variations tried in these experiments, apparently does not change the nature of the strain. But perhaps, after all, only a non-rotational strain could develop under

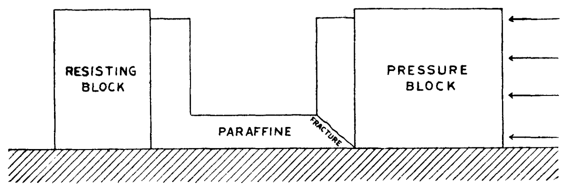

FIG. 14.—Block similar in shape to that shown in Figs. 12 and 13, but composed of paraffine. A 45° fracture developed.

the conditions of these experiments, since the pressure block is guided rigidly forward by the controlling flanges of the machine and so cannot turn. But one may conclude, nevertheless, that a piled-up mass having a higher standing cross-section to be pushed forward, does not, of itself, add a rotational element to the strain when laterally compressed, nor, so far as this principle is concerned, does it lower the angle of fracture.

How rotational strain develops fracture.—To show how a rotational strain will deform such a block as was used in the experiment just described, another block of paraffine was cast in the same mold and subjected to a rotational strain in the following manner. As before, the pressure was applied from the same long side, but instead of being applied against the whole surface of that side it was applied only to the upper half of it. The resisting block, as before, buttressed the whole of the shorter left-hand side. With the opposing forces acting horizontally at quite different elevations, a rotational couple was developed. As the strain slowly increased the paraffine

near the pressure block first yielded somewhat by plastic deformation. Then, as a result of the shearing stresses, it started to break along a very low angle of fracture near the bottom of the block (Fig. 16, break *A*). The experiment was stopped at this point and the block removed for study. After a rest of a few days the deformed block was again placed in the crushing machine and

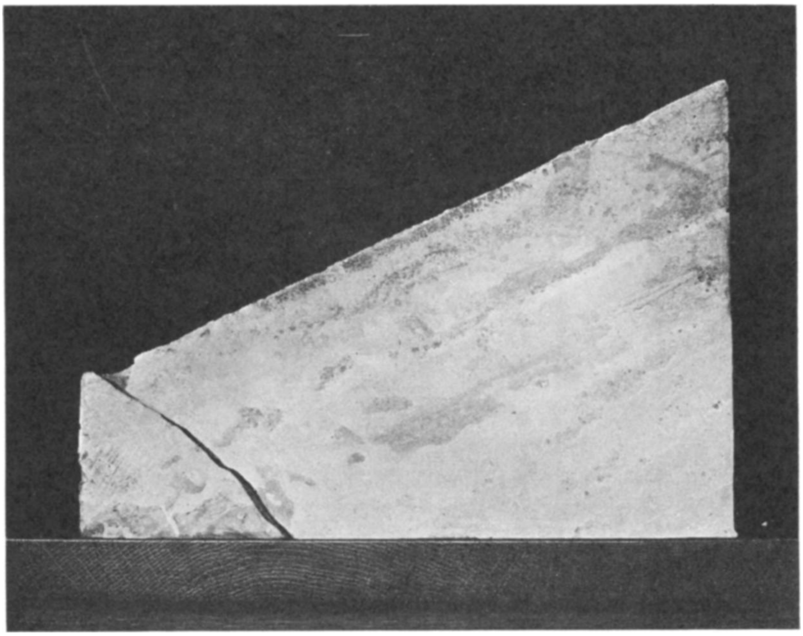

FIG. 15.—Deformation of specially shaped paraffine block under non-rotational strain. Pressure applied uniformly upon right-hand face. Fracture averages 42°.

pressure applied as before. But instead of further splitting along the old line of breakage near the bottom of the block, an entirely new break occurred at a much higher level (Fig. 16, break *B*). This new fracture extended completely across the block. Though irregular in detail, its general direction was very close to horizontal. To verify these results, a new block of paraffine was cast in the same mold and pressure was again applied in the same way. The result again was breakage along a nearly horizontal shearing plane (Fig. 16, break *C*). In breaking out at the surface, however, the fault plane,

in both cases, turned upward, producing a considerably steeper angle in the immediate vicinity of the surface.

Experiments therefore show that the effect of a strong rotational strain, even in homogeneous material, is to produce shearing and complete rupture, essentially parallel to the direction of the applied force. If the thrusting be in a horizontal direction, the plane of rupture will approach horizontality. In these experiments it was noted that the low-angle shearing required fewer turns of the screw and thus the application of less force than the 45° fracture from

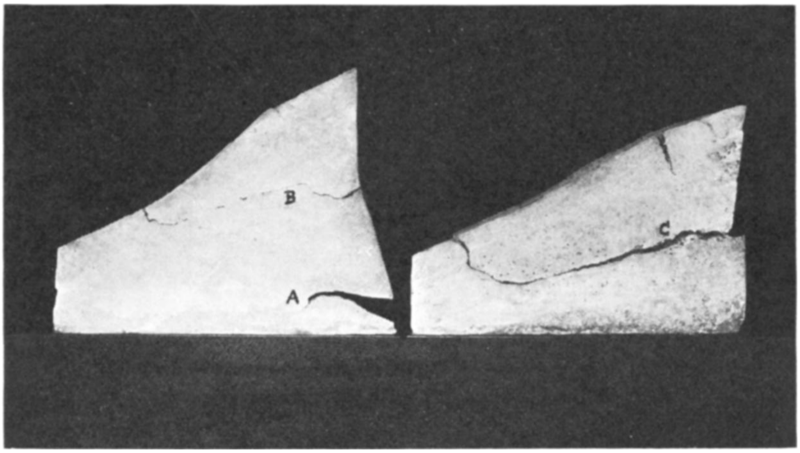

FIG. 16.—Deformation of paraffine blocks (same mold as block in Fig. 15) under rotational strain. Pressure applied only to the upper half of the right-hand face. The fracturing, though irregular, was not far from horizontal.

non-rotational strain. This merely bears out the well-known fact that the resistance of materials to shearing stresses is much less than to direct compressive stress. Hence the disposition to shear if conditions allow.

Lessening the resistance above.—Deformation by rotational strain may thus be developed in homogeneous material by sufficiently increasing the effective differential stress in the upper portion of the mass with respect to that in the lower portion. It is the greater unbalanced pressure in one portion over another which is effective. This unbalancing of pressure may be accomplished in several ways. Within the earth it may be produced either by increasing the lateral

thrusting in the upper portion or by lessening its resistance, while the lower portion remains unchanged. It may also be developed by diminishing the thrust below or by increasing the resistance in the lower part, while conditions in the upper portion remain essentially the same. Or it may be accomplished by some combination of these. The first process facilitates deformation in the upper part; the second retards deformation in the lower part. Whatever affects the ratio influences the character of the deformation. The greater the difference developed the greater the shearing tendency. The intensity of thrusts and the resistance at different horizons in the earth should therefore be a vital factor in determining shearing.

At the present time the location and intensity of lateral thrusts in the earth are so imperfectly understood that a treatment of that topic is reserved for further information. Rather more, however, is known concerning the resistance offered. Factors which either lessen the resistance above, or increase it below, may play a part in overthrust faulting.

The resistance above may be diminished in several ways. The erosion-thrust of Willis and Hayes already discussed is a clear-cut illustration of how it may be accomplished in heterogeneous materials. Resistance above is here reduced by erosion which removes the heavy, competent upper layers from the crest of an anticline. The resistance of the remnants of the upper layers to forward movement having been sufficiently diminished in this way, this more movable portion shears nearly horizontally along a bedding plane as a line of weakness (see Fig. 2). Shearing along bedding planes and the control of overthrusts by differences in the competency of the beds are related phenomena.

In homogeneous material the resistance above is lessened by other means. The experiments of Cadell indicated that before the low-angle overthrust occurred there was first slice faulting and the piling up of slices. Slice faulting to a remarkable extent was associated with the Scottish overthrusts and to a certain extent with those in the southern Appalachians. If the mere piling up of materials, as such, does not introduce a rotational element to the strain and so lower the angle of fracture, nevertheless the repeated slice faulting and moving of fault blocks do have an effect upon

the resistance of the faulted strip. The slicing and secondary shattering would seem to weaken the superficial sheet which has suffered the faulting. It may be perhaps that the superficial shell, freer to move as a general mass than it was before slicing, while the lower, deeper levels have not been equally affected by what has taken place, now finds it easiest to slide bodily forward over the less movable lower portion. If this be true, it would make the rupturing by the preparatory slice faulting far more important in the development of low-angle overthrusts than the piling up of material.

Greater resistance and drag below.—With horizontally directed compressive stresses in operation rotational strains would also tend to be produced by the co-operation of any factor which increased the resistance of the deeper portion of the rock mass involved, while the resistance of the more superficial portion to such stresses remained the same. The far-reaching experimental studies of Dr. Adams and his colleagues have shown that, on account of the increasing rigidity of the rocks due to cubical compression from the weight of overburden, resistance to deformation in the earth should increase with increasing depth below the surface.[1] It is concluded that with increasing depth greater and greater stress differences are required to deform the rocks. From this principle it would seem to be a legitimate deduction that, for a lateral thrust of given magnitude, rock deformation should take place more readily near the surface of the earth than at a greater depth beneath the surface, and that in any case (barring the effects of local heating, or liquefaction) deformation should become less with depth, unless the magnitude of the stress differences which cause the thrusting increases as rapidly with increasing depth as does the resistance offered by the rocks.[2]

[1] Frank D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (1912), 97–118.

[2] Since this was written, the principle of increasing resistance to deformation with depth below the surface of the earth has been strongly affirmed by Adams and Bancroft as the result of further experimental researches. (See Frank D. Adams and J. Austen Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation, and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV [1917], 597–637. Also Louis Vessot King, "On the Mathematical Theory of Internal Friction and Limiting Strength of Rocks under Conditions of Stress Existing in the Interior of the Earth," *Jour. Geol.*, XXV [1917], 638–58.)

In general, so far as these principles hold, there should be a tendency, strong or feeble according to the quantitative factors, for surficial shearing over a less movable portion below. Rotational strains thus brought into being might conceivably in some cases be a primary cause of low-angle shearing, or in other instances might co-operate as a secondary factor with other more important causes in producing a similar result.

Many glaciers, notably those in North Greenland, have developed in places horizontal shearing planes which are often grouped into distinct zones.[1] The englacial drift is definitely arranged along these planes of movement, and this in turn influences the rate of melting on the steep edge of the glacier, so that these planes of shear have, in many instances, become very conspicuous. These lines of débris are especially prominent in the lee of an embossment of rock over which the glacier has just passed. In most cases the shearing planes may be interpreted as due to the greater resistance of the rock knobs below. They seem to be further developed by the increased load of débris in the lower part of the glacier and by drag on the bottom beneath the moving mass. The rotational strain thus engendered causes nearly horizontal slippage of the upper portion over the lower. Where formed in the lee of an embossment of rock another factor enters to increase the rotational element. The rock mass protects the lower portion of the glacier from much of the push which the upper portion is receiving.[2] Thus while the upper portion of the ice is free to move forward, not only is the resistance of the lower portion of the ice to forward motion increased, but at the same time the actual thrusting to which that portion is subjected is diminished.

C. E. Decker has described various minor folds and small thrust faults, mostly of Quaternary age, which affect the strata close to the surface in northeastern Ohio and northwestern Pennsylvania.[3] The fault planes of these thrusts are commonly inclined at low angles (Fig. 17). If their proximity to the surface is of real

[1] T. C. Chamberlin, "Glacial Studies in Greenland," *Bull. Geol. Soc. Amer.*, VI (1894), 203–10.

[2] T. C. Chamberlin, *op. cit.*, pp. 207–8.

[3] Charles E. Decker, unpublished manuscript.

significance, it would suggest a strong tendency of layers near the surface to shear over less movable layers below.

E. EFFECT OF WEIGHTING

Although the piling up of faulted slices does not of itself cause the development of rotational strain, when the mass is subjected to horizontal compression, it may indirectly bring about that result by weakening the resistance of the upper portion owing to the

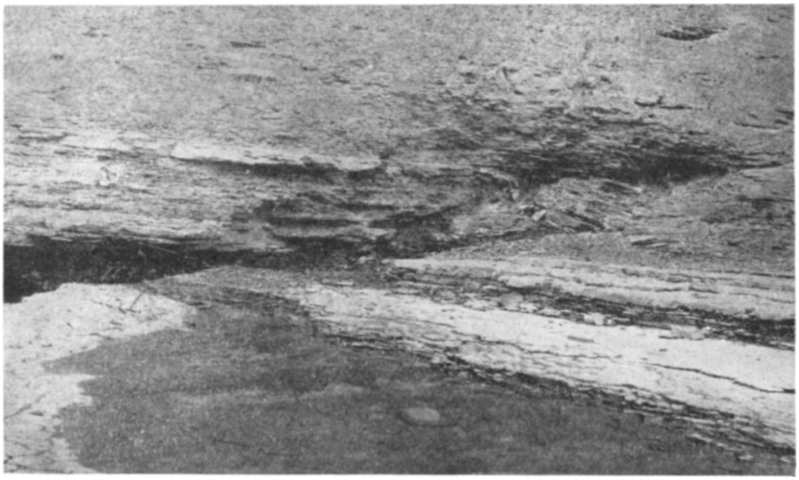

FIG. 17.—Thrust fault in Chagrin shales. On Paine Creek, 6 miles east of Painesville, Ohio. Fault plane dips 15° S.W. Throw 1 ft., heave 2 ft. 11 in. Charles E. Decker.

preliminary fracturing. If, in addition, the mass piled up is of sufficient magnitude, it may theoretically affect the result in another way owing to the fact that the additional weight of the piled-up mass adds a new force at right angles to the horizontal thrust. Figure 18 will illustrate the behavior of this force. In this diagram the horizontal thrust was taken to be three times the vertical force due to gravity. The resultant of these two forces will be inclined downward 18° 26′ from the horizontal. Fracturing as the result of these two forces will be determined by the direction of this resultant of forces. As this is inclined 18° 26′ downward from the horizontal, faulting, even though it should take

place at an angle as high as 45° upward from the resultant of the forces, would still be only 26° 34′ from the horizontal. The relative magnitude of the horizontal thrusting force and the weight of the heaped-up mass determines how much the angle of faulting, under the given conditions, will be diminished from 45°. If the weight of the load gave a force equal to half that of the lateral thrust, the angle would be lowered because of this factor to the extent of 26° 34′, thus making it 18° 26′ from the horizontal. If the vertical force due to the extra load amounted to one-fourth the horizontal thrust, the angle of faulting would be lowered approximately 14° 2′, leaving it 30° 58′ from the horizontal. The resulting angle for the various stress ratios may readily be calculated.

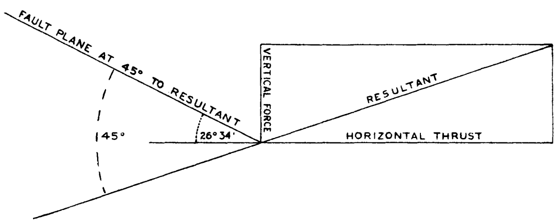

FIG. 18.—Diagram to illustrate the position of a fault plane inclined 45° to the resultant of forces. The horizontal thrust is here taken to be three times the vertical force. Result: the fault plane will be inclined 26° 34′ from the horizontal.

The effect of adding load, and hence additional force acting downward, is to subject the material under thrust to increased cubical compression. According to the principles so strikingly worked out by Adams and his colleagues, the effect of this should be to increase the internal resistance of the material and thus necessitate a much greater stress difference to initiate deformation than would be required without the additional load. Greater stress difference necessitates much greater lateral thrusts. As a result faulting may be hindered or even prevented altogether until much greater thrusts are developed. It may also, in consequence, be caused to take place elsewhere, as, for example, some distance beyond the edge of the loaded area. In our experiments with weighting the faulting most frequently appeared at the surface close to the border of the weighted portion, the fault plane dipping

under the heavily burdened portion (see Fig. 19). But in these experiments the loads were relatively light.

A load light in proportion to the horizontal stress will thus influence the angle of fracture, depending upon the ratio of vertical and horizontal stresses. A load very great in proportion to the horizontal stress will prevent faulting altogether within the loaded area. The influence of the load upon the angle of thrusting will therefore reach a maximum value somewhere between a load which

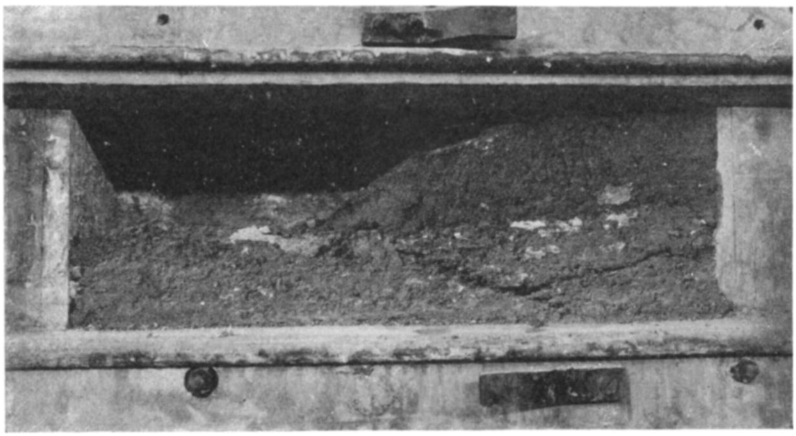

FIG. 19.—Effect of local weighting in locating the position of faults. The material to be faulted was clay stiffened with plaster; the added load was damp sand. In experiments of this sort the fracture plane most frequently appeared at the surface close to the edge of the piled-up overburden.

is light and a load which is heavy relative to the horizontal stress. What the proper ratio for the maximum effect will be cannot well be determined until more is known of the limiting strength of rocks under stress.[1] Some idea, however, may be gained possibly by a rough inspection of the factors involved. The stress difference necessary to cause faulting at a given depth in the earth would need to be sufficient to exceed the sum of the crushing strength of the given rock at the surface, plus the weight of overburden which must be lifted, plus again the increased strength of the material

[1] Louis V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior," *Jour. Geol.*, XX (1912), 119–38.

resulting from the compression under the load. Suppose there were 10,000 feet of rock piled up above the plane along which the fault is to occur. Assuming a specific gravity of 2.7 for the rock, the pressure resulting from this column will amount to about 11,760 lbs. per square inch. If the stress along the axis of greatest stress, which is here horizontal, be taken to be three times this, it would need to be 35,280 lbs. per square inch. As the axis of least stress is vertical, the stress difference would amount to 23,520 lbs. per square inch. To cause faulting, this stress difference must equal the crushing strength of the rock under surface conditions augmented by the increased strength of the material induced by the hydrostatic pressure or cubical compression. This increased strength because of the depth is considerable, but pending more work of the type carried on by Adams and his colleagues this is not easily evaluated.[1]

However, this stress difference clearly would not be sufficient at this depth to deform the stronger rocks, like granite, and probably not rocks of average strength, though very likely it would be sufficient to deform the weaker rocks. Under these conditions, if the horizontal thrust were less than three times the vertically acting force, the stress difference would be proportionately still less effective in deformation. A ratio of more than three to one would, on the contrary, be more effective. A ratio of thrust to the weight of not less than three to one would seem to be required for extensive faulting through rock formations of average strength under a load ranging up to 10,000 feet of rock. This might lower the angle of faulting by 18° or less. But this reduction in angle from 45° falls far short of developing the approximately horizontal slippage planes of the great overthrusts. With loads greater than 10,000 feet of rock, the resistance of the underlying rock is still further increased. While the increase in resistance probably does not mount up in direct proportion to the increase in balanced pressure, nevertheless for any thicknesses of rock likely to be piled up by diastrophic agencies there probably would not be a very radical change in the ratio of axes of stress necessary for faulting. At

[1] More data are now available. See Frank D. Adams and J. Austen Bancroft, *Jour. Geol.*, XXV (1917), 597–637; also Louis Vessot King, *ibid.*, XXV (1917), 638–58.

best only a part of the lowering of the angle from 45° can be explained in this way.

If the low angle of the great overthrusts were solely a matter of load steadily accumulated by piling up slice fault blocks, then each successive slice fault should break through at a progressively lower angle. There should be a complete gradation from the first-formed fault near 45° to the final overthrust approaching horizontality. While some progressive lowering of the angle of the successive slice faults is to be noted in some Scottish Highland sections and elsewhere, nevertheless there appears to be a great final jump from the minor slice faults to the great horizontal overthrust.

F. RÉSUMÉ

The great overthrusts which are now coming to be recognized as a prevalent and commanding type of mountain structure are the result of conditions differing considerably from those which produce ordinary reverse faults. The distinguishing features of the overthrusts are the extremely low angle, which often approaches horizontality, and the very great displacement along the plane of slippage. The great displacement is made easier by the gentle slope of the fault plane. The low angle of the fault plane is the net result of the operation of several factors. Among the factors which will lower the angle of faulting from the theoretical 45° may be listed the following:

1. The normal or direct stress which, along planes inclined 45° to the line of application of the force, has an intensity as great as that of the tangential stress. It acts as a frictional resistance to shearing by the tangential stress. The lower the angle of the fracture plane, the less will be the frictional resistance due to the normal component of the stress. Hence the tendency to fracture at angles below 45°.

2. Rotational strain, which will lower one of the planes of no distortion (shearing plane) from 45° in pure non-rotational strain to 0° in the extreme case of rotational strain. Rotational strains may be developed from horizontal compressive stresses: (*a*) in homogeneous material: (1) by any factors which will increase the intensity of the tangential stress in the upper portion of the mass

undergoing thrusting with respect to that in the lower portion; (2) by any factors which will lessen the resistance in the surficial portion without proportionately changing that below; and (3) by any factors which will increase the resistance of the deeper portion of the zone subject to thrusting while the upper portion remains freer to yield; (*b*) in heterogeneous material by bedding, or similar structures, which present differences in competency of the right sort and thus call into operation some of the foregoing factors.

3. Preliminary piling up of material in the first stages of deformation, thus increasing the load and the vertically acting gravitative force. The combination of the horizontal thrusting force and the vertical gravitative force gives a resultant which is inclined downward from the horizontal. Even should faulting take place in a plane 45° from this resultant, it would still be inclined less than 45° from the horizontal.

4. Possible minor factors, as heterogeneity of material, length of deformed mass with respect to its other dimensions (after analogy of long column), shape of deformed mass, etc.

To these factors, operating in various combinations according to the individual peculiarities of each particular case, are attributed the low-angle fault planes of the great overthrusts.